

Modelling the time dependence of the TeV γ -ray source at the Galactic Centre

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ABSTRACT

The physical mechanism behind the TeV γ -ray source observed at the centre of the Galaxy is still unknown. One intriguing possibility is that the accretion flow onto the central supermassive black hole is responsible for accelerating protons to TeV energies which then diffuse outward to interact with molecular gas at distances of ~ 1 pc. Here, we build on our earlier detailed calculations of the proton transport to consider the time and energy dependence of the TeV signal following a burst of particle acceleration at Sgr A*. We find that, due to the strong energy dependence of the proton diffusion, any variability in the particle acceleration rate will only be visible in the TeV signal after a delay of ~ 10 yrs, and only at energies $\gtrsim 10$ TeV. If the accelerator is long-lived it must have been running for at least 10^4 yrs and have a hard proton injection spectrum of $\alpha = 0.75$ (where $dn/dE_{inj} \propto E^{-\alpha}$) in order to produce the correct amount of high energy γ -ray flux. This rapid diffusion of high energy protons also rules out the possibility that the observed TeV source is directly related to the period of increased activity of Sgr A* that ended ~ 100 yrs ago. However, a good fit to the observed H.E.S.S. data was found with $\alpha = 2.7$ for the scenario of a brief (\sim few year long) burst of particle acceleration that occurred ~ 10 yrs ago. If such bursts are common then they will keep the TeV source energised and will likely produce spectral variability at $\gtrsim 10$ TeV on $\lesssim 5$ yr timescales. This model also implies that particle acceleration may be an important mechanism in reducing the radiative efficiency of weakly accreting black holes.

Key words: ISM: individual: Sgr A* — Galaxy: centre — γ -rays: theory — radiation mechanisms: nonthermal

1 INTRODUCTION

The centre of the Milky Way galaxy is located at the position of the radio source Sgr A*, and contains a supermassive black hole with a mass now measured to be $4.5 \times 10^6 M_{\odot}$ (Ghez et al. 2008). The proximity of the Galactic centre — at a distance of only 8.4 kpc (Ghez et al. 2008) — allows an unprecedented opportunity to study in detail the complex physics that occurs in the environments around supermassive black holes. The recent discovery of TeV γ -rays emanating from a region only ~ 3 pc from Sgr A* (Aharonian et al. 2004; Kosack et al. 2004; Tsuchiya et al. 2004; Albert et al. 2006; Aharonian et al. 2006b) is an excellent example of the numerous physical puzzles presented by the Galactic centre. Although the centroid of the Galactic centre TeV source is located only $\sim 8''$ from Sgr A* (Acero et al. 2010), the origin of the TeV photons is not understood. There are two main pathways to produce TeV γ -rays: the first is a hadronic process where protons with TeV energies scatter off lower energy protons producing pions ($pp \rightarrow p\pi^0\pi^{\pm}$), with the π^0 s quickly decaying into two γ -ray photons.

The energetics of the collisions generally produce γ -rays with energies $\sim 10\times$ less than the incident TeV proton. The second mechanism is via inverse Compton scattering of UV photons off of TeV electrons. Both mechanisms require a powerful particle accelerator to produce the high-energy particle population. Unfortunately, the region around Sgr A* contains several such accelerators, including a supernova remnant (Crocker et al. 2005), a pulsar wind nebula (Wang, Lu & Gotthelf 2006; Hinton & Aharonian 2007), and Sgr A* itself (Atoyan & Dermer 2004; Aharonian & Neronov 2005a,b; Ballantyne et al. 2007a). The centroid of the TeV source has now been measured with sufficient accuracy to exclude the Sgr A East supernova remnant as the source of the emission (Acero et al. 2010); however, the pulsar and the black hole remain plausible sources of the high-energy particles responsible for the TeV emission.

The temporal relationship between particle acceleration and TeV emission is one way to discriminate between the various origins of the high-energy particles. Sgr A* has recently exhibited flares on timescales as short as minutes at both X-ray and near-IR wavelengths (e.g., Porquet et al. 2003; Eckart et al. 2006). This timescale indicates the flaring region must be extremely close to the

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black hole event horizon, one of the possible sites of particle acceleration (Liu et al. 2006). Thus, the expectation is if Sgr A* is the origin of the TeV particles, the TeV γ -rays should be variable, and possibly be coincident with the flares observed at lower energies. However, no variability of the TeV source has ever been observed on timescales ranging from 30 minutes to years (Rolland & Hinton 2005; Albert et al. 2006; Aharonian et al. 2008). Moreover, during a coordinated monitoring campaign with *Chandra*, the H.E.S.S. instrument did not detect any increase in TeV γ -ray emission during a X-ray flare (Aharonian et al. 2008). Thus, the γ -rays are unlikely to be produced in the same region as the relativistic X-ray emitting electrons (i.e., within ~ 100 Schwarzschild radii of the black hole). This fact must be explained by any model for the TeV γ -rays, and seems to support the scenario where the γ -rays are associated with electrons accelerated by the pulsar wind nebula.

However, protons may be accelerated close to the black hole, but be converted to γ -rays only after travelling a significant distance away from the acceleration region (e.g., Atoyan & Dermer 2004; Aharonian & Neronov 2005b; Ballantyne et al. 2007a). In the scenario presented by Ballantyne et al. (2007a) proton acceleration was assumed to occur at distances of only ~ 20 – 30 Schwarzschild radii from the black hole (e.g., Liu et al. 2006). The particles would then diffuse away from Sgr A* through the magnetised turbulent ISM, until possibly colliding with the dense molecular gas in the circumnuclear disk (CND; e.g., Montero-Castaño et al. 2009) at a distance of 1–2 pc. Ballantyne et al. (2007a) modelled this process in detail, paying close attention to the propagation of the high-energy protons, and obtained a good fit to the observed TeV spectrum. A key finding of this calculation was the strong energy dependence of the proton interaction with the CND (the site of the γ -ray production). Only $\sim 5\%$ of the 100 TeV protons interacted with the CND to produce γ -rays, with this rising to $\sim 40\%$ at 10 TeV and $\sim 70\%$ at 1 TeV. The higher energy protons scattered far fewer times in the ISM than the low energy ones and therefore were less likely to encounter the CND and produce γ -rays. Thus, a high energy roll-over in the TeV spectrum at energies $\gtrsim 10$ TeV is a generic prediction of the hadronic model, and a relatively flat proton spectrum is required to compensate for the low interaction rate between the high energy protons and the CND. Ballantyne et al. (2007a) only considered the steady-state γ -ray flux and spectrum, but it is clear that the significant energy and geometric dependence of the diffusion and scattering processes will lead to an interesting time dependence of the γ -ray flux if there is some change at the acceleration site. It is clearly important to quantify the spectral and time dependence of the expected TeV signal to allow testing of the hadronic model with the continued γ -ray monitoring of Sgr A*. In addition, the time evolution of the γ -ray spectrum may be relevant to the recent Fe K α line maps of the Galactic centre environment which indicate that Sgr A* was more luminous ~ 100 years ago (e.g., Muno et al. 2007; Inui et al. 2009; Ponti et al. 2010; Terrier et al. 2010). These observations raises the possibility that the current observed TeV emission is related to an earlier, more active state of the black hole and not its current state.

This paper makes use of the proton transport calculations performed by Ballantyne et al. (2007a) to investigate the time and energy dependence of the TeV γ -ray emission in the scenario where the protons are accelerated very close to the black hole. We will quantify the variability timescale expected for the TeV emission in this model and explore the possibility that the current TeV flux is related to an earlier outburst of Sgr A*. The next section details how the time dependence of the TeV flux was computed. Section 3

presents the results, while Section 4 contains our discussion and conclusions.

2 CALCULATIONS

Ballantyne et al. (2007a) calculated over 220,000 proton trajectories in a $6 \text{ pc} \times 6 \text{ pc} \times 6 \text{ pc}$ cube consisting of 10^6 equally spaced cells centred on the Galactic centre. Details of the computations of the proton transport and γ -ray production can be found in that paper. The γ -rays are produced from clumps of high density ($n_{\text{H}} > 3000 \text{ cm}^{-3}$) gas in a model CND that has an inner radius of 1.2 pc from Sgr A* and a thickness of 1 pc. The spectrum of protons that escapes the acceleration region at Sgr A* is a power-law with index α (i.e., the injected proton spectrum is $dn/dE_{\text{inj}} \propto (E/E_{\text{min}})^{-\alpha}$, where $E_{\text{min}} = 1 \text{ TeV}$). The steady-state calculation of Ballantyne et al. (2007a) found a good fit to the H.E.S.S. TeV data with $\alpha = 0.75$, a much flatter spectrum than is expected from traditional particle acceleration mechanisms (where $\alpha \sim 2$ – 2.5). We compute γ -ray flux (in $\text{ph m}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$) at 31 logarithmically spaced energies: $\log(E/\text{eV}) = 11, 11.1, \dots, 13.9, 14$.

The time step used in the proton transport computations varied between a small fraction of a year for the lowest energy particles to just over a year for protons with energies close to 100 TeV. Thus, variations in the TeV spectrum and flux can only be calculated for timescales greater than ~ 1 yr. The time dependence of the γ -ray flux will be investigated in two ways. First, the particle accelerator located at the origin is assumed to turn on at $t = 0$ and remain on at a constant rate. All proton trajectories are followed for an observed time t , and the optical depth to scattering with CND gas during this time is recorded. After a complete census of the optical depth to proton-proton scattering in the dense gas is determined, the total γ -ray flux in multiple energy bands is then calculated. The limiting time t is increased until the fluxes reach the observed values determined by the steady-state model.

A second calculation is performed to investigate the response of the TeV flux to a burst of particle acceleration lasting Δt years. The proton trajectories are followed and the γ -ray flux calculated in the time interval $(t, \Delta t + t)$ with t increasing from 0 to 105 yrs in steps of 5 yrs. This computation is performed for bursts of activity lasting $\Delta t = 3, 10, 30, 100$ and 300 yrs. This experiment will help determine if the current observed TeV source may have been caused by an earlier period of activity around Sgr A*.

3 RESULTS

3.1 Rise Time to a Constant Flux

Figure 1 plots the γ -ray flux as a function of time in three different TeV energy bands. This figure shows the fluxes as fractions of the observed H.E.S.S. values as determined by the steady-state model (Ballantyne et al. 2007a). The Lorentz force of the magnetic field on a proton is proportional to $1/\gamma$, where γ is the Lorentz factor of the proton, so high energy protons spend less time random walking around the interstellar medium and reach the dense gas much more rapidly than the lower energy particles. Therefore, it only takes ~ 10 yrs for the 10–100 TeV flux to reach a significant fraction of its steady-state value. The lower energy protons take much longer to diffuse outwards. Indeed, after the particle accelerator has been operating for 10 yrs the 0.1–1 TeV flux has reached only $\sim 3\%$ of its final value. The accelerator must run for over

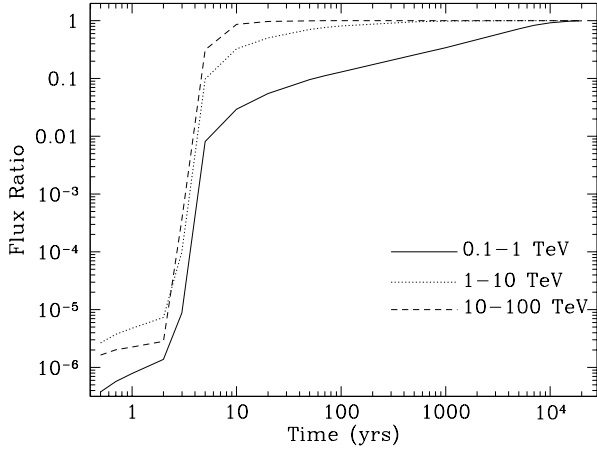


Figure 1. The time evolution of the Galactic centre TeV source in three different energy bands. Proton acceleration is assumed to begin at the origin (i.e., very close to Sgr A*) at $t = 0$ and continue at a constant rate. The spectrum of protons injected into the interstellar medium is a power-law with spectral index $\alpha = 0.75$. The fluxes are plotted as a fraction of the observed H.E.S.S. values. Due to the rapid diffusion time of the very high energy protons, the 10–100 TeV flux reaches $> 90\%$ of its steady-state value after only ~ 10 yrs. In contrast, it takes several hundred years for the 1–10 TeV flux and $\sim 10^4$ yrs for the 0.1–1 TeV flux to reach the same fraction of the steady-state value. The large increase in the flux ratios after ~ 5 yrs corresponds to the proton ‘front’ reaching the CND surrounding Sgr A*.

10^4 years¹ for enough protons to interact with the molecular gas to account for the observed H.E.S.S. flux. The normalisation of the injected proton spectrum was chosen so that these equilibrium fluxes would match the observed values. If a higher normalisation was chosen (i.e., the proton luminosity produced by the Sgr A* accelerator was higher) then the timescales for the fluxes to match the observed values would be shorter, but the steady-state fluxes would be greater than what is observed, violating the initial assumption of our scenario (that the observed TeV source is due to an accelerator has been operating at a constant level for a long time).

After the accelerator has been operating for about 3 yrs, the first protons start interacting with the CND and produce TeV γ -rays. As seen in Figure 2, the TeV spectrum produced at this time would be hard with a 0.16–30 TeV photon index $\Gamma \sim 1.6$ (where photon flux $\propto E^{-\Gamma}$), as only a small fraction of the low energy protons would be on fortuitous trajectories to interact with the high density gas at this early stage. The spectrum softens steadily over the next 10^4 years as the lower energy protons reach the CND and produce γ -rays.

Several conclusions can be drawn from this experiment. First, if there is a proton accelerator close to Sgr A* and it either switches on or increases its acceleration rate (i.e., a flare of protons), the resulting γ -rays will not be detected for ~ 10 yrs and only in the very high energy 10–100 TeV band. It will take over a century for the flare to be seen in 1–10 TeV γ -rays. Therefore, the null result found in the coordinated X-ray/TeV monitoring of Sgr A* (Aharonian et al. 2008) indicates that the X-ray and TeV photons are being produced in different regions, but does not rule out

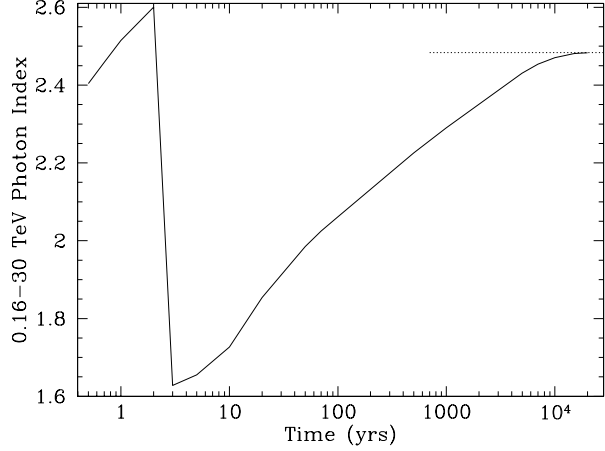


Figure 2. The time evolution of the 0.16–30 TeV photon index for the scenario where a constant proton accelerator is ignited at the origin at $t = 0$. The dotted line corresponds to a photon index of 2.48, the value derived from the best fit model to the H.E.S.S. data. This value is somewhat steeper than the observed photon index of 2.25 ± 0.10 (Aharonian et al. 2006b) because of the roll over in high energy γ -rays predicted by the model. As the low energy protons diffuse much slower than the higher energy ones, the TeV spectrum softens slowly with time, and does not reach the observed value for over 10^4 yrs. The sharp increase and decrease of the photon index after only 2 years is due to the interaction of a small number of primarily low-energy protons with one dense clump of gas that is located only ~ 0.1 pc away from the origin.

that Sgr A* is ultimately responsible for the proton acceleration. These results show that time variability of the TeV source is likely to be observed only in the 10–100 TeV band and on decade-like timescales. If such variability was observed, however, it would give strong support to a high-energy diffusion process producing the γ -rays and thus the hadronic and Sgr A* model for the TeV emission. On the other hand, if no variability of the TeV source is ever detected, it still will not rule out Sgr A* as the site of particle acceleration, but it will imply that this accelerator must be operating at a relatively constant rate for $> 10^4$ yrs.

3.2 Is the TeV Source Connected to Past Activity of Sgr A*?

In the hadronic model for the TeV source, the γ -rays are produced from protons that have diffused outwards from the acceleration site close to Sgr A*. The previous section showed that this diffusion can cause a significant delay between when the protons were accelerated and when they produce γ -rays. Given the evidence that points to a more luminous black hole at the Galactic centre $\gtrsim 100$ yrs ago, it is interesting to consider the possibility that the current observed γ -ray source was caused by this earlier activity. Unfortunately, Figure 3 rules out this possibility. The rapid diffusion of the > 10 TeV protons causes the resulting γ -ray spectrum to soften rapidly. As discussed above, the highest energy protons scatter off the CND and produce high energy γ -rays only ~ 10 yrs after being injected into the interstellar gas. Increasing the duration of the burst of particle acceleration does not improve this situation as long as the observations are being made following the end of the burst. This is because it is only the protons that were injected within the last decade that produce the high energy $\gtrsim 10$ TeV γ -rays. Fig. 3 shows the results for an injected proton spectrum with $\alpha = 0.75$. The same calculations were also performed with more traditional values of $\alpha = 2$ and 2.5, but, as the diffusion properties of the

¹ This is $\sim 1000\times$ shorter than the estimated lifetime of the CND (Montero-Castaño et al. 2009); thus, these timescales are not effected by the static gas model for the CND and surrounding ISM.

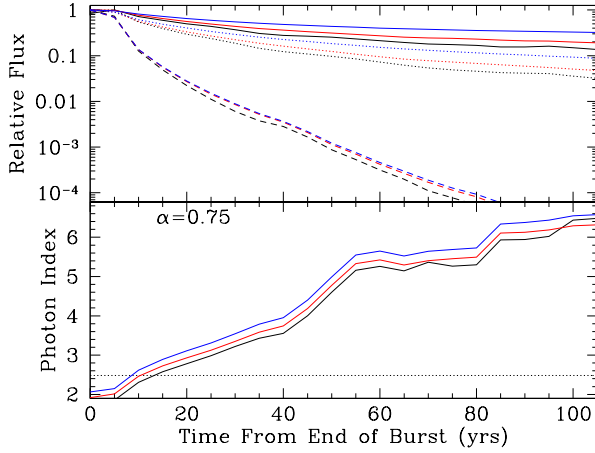


Figure 3. The time evolution of the TeV γ -ray source following bursts of proton injection that lasted 10 (black lines), 30 (red lines) and 100 (blue lines) year. The top panel plots how the 0.1–1 (solid line), 1–10 (dotted line) and 10–100 (dashed line) TeV fluxes evolve with time, with each band normalised to its maximum flux. The bottom panel shows the time evolution of the 0.16–30 TeV photon index. The dotted line corresponds to a photon index of 2.48, the value derived from the best fit model to the H.E.S.S. data. These results were computed assuming $\alpha = 0.75$.

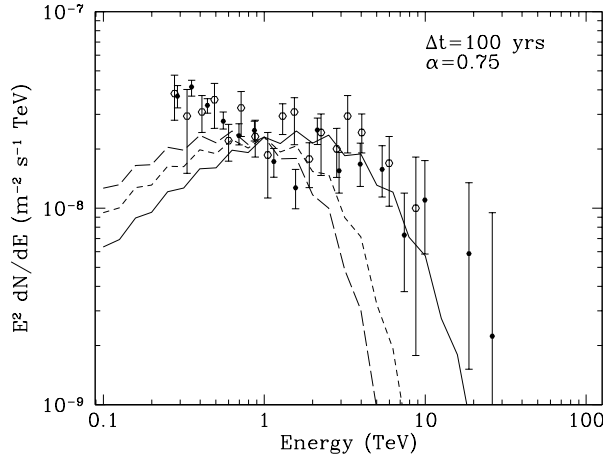


Figure 4. The TeV spectrum produced at 10 (solid line), 50 (short-dashed line) and 100 (long dashed-line) years after a 100 year-long burst of proton acceleration close to Sgr A*. The 2003 H.E.S.S. data are plotted as the open points, and the 2004 H.E.S.S. data are plotted as the solid points (Aharonian et al. 2004, 2006b). All three spectra have been normalised to a flux of $2.3 \times 10^{-8} \text{ m}^{-2} \text{ s}^{-1} \text{ TeV}$ at 1 TeV.

protons are independent of α , the conclusion is unchanged: if the observed TeV signal is related to accretion onto Sgr A*, it cannot be caused by a burst of protons produced $\gtrsim 100$ years ago during the period of greater X-ray luminosity.

Figure 3 indicates that the TeV spectrum may have the right shape ~ 10 –15 years after a burst; however, comparing these spectra to the H.E.S.S. data illustrates another feature of the proton diffusion in the Galactic centre. Figure 4 plots the TeV spectrum produced at 10, 50 and 100 yrs following a 100 year-long burst of proton acceleration at the Galactic centre. This figure shows that at energies less than 1 TeV, all three spectra retain the hard shape of the injected proton spectrum, in marked contrast to the observed spectrum at those energies. Thus, even though the average spec-

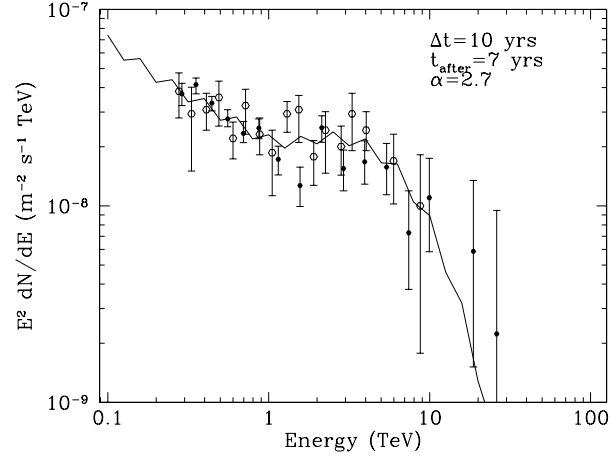


Figure 5. The TeV spectrum produced 7 years after the end of a 10 year-long burst of proton acceleration close to Sgr A*. The injected proton spectrum has a spectral index of 2.7. The spectrum has been normalised to a flux of $2.3 \times 10^{-8} \text{ m}^{-2} \text{ s}^{-1} \text{ TeV}$ at 1 TeV. The 2003 H.E.S.S. data are plotted as the open points, and the 2004 H.E.S.S. data are plotted as the solid points (Aharonian et al. 2004, 2006b).

tral slope 10 years after the burst is close to the observed value, the actual shape of the spectrum does not describe the data. The reason for this very hard spectrum at $\lesssim 1$ TeV is that the low energy protons take a very long time to diffuse outward to the CND (see Fig. 1). The low energy γ -rays that make up the plotted spectra are made up from very few interactions of protons and dense clouds. As time passes, more of these interactions occur and, since a very high percentage of the low energy protons interact with the molecular gas, the 0.1–1 TeV spectrum rises steadily. However, as seen in Fig. 1, it will take several thousand years before the majority of injected low energy protons have interacted with the CND. Therefore, the burst scenario with $\alpha = 0.75$ leaves us with a catch-22 situation: the high energy γ -ray spectrum can only be matched ~ 10 yrs after the burst, but the low energy TeV spectrum will not have the right shape for several thousand years after the burst.

These results lead to an interesting possibility: as the low energy TeV spectrum closely follows the injection spectrum after a burst of protons, is it possible to fit all of the H.E.S.S. data with a softer proton injection spectrum? This would only work for burst durations $\lesssim 10$ yrs so that high energy γ -rays would make up a significant fraction of all the proton interactions. We searched for such a solution using χ^2 fitting to the observed H.E.S.S. data. All model spectra were normalised to a flux of $2.3 \times 10^{-8} \text{ m}^{-2} \text{ s}^{-1} \text{ TeV}$ at 1 TeV with α and the time since the end of the burst being free parameters. With $\Delta t = 10$ yrs we found a good fit ($\chi^2/\text{d.o.f.} = 43.4/31$, where d.o.f. = degrees of freedom) at 7 yrs after the burst and $\alpha = 2.7$. The resulting spectrum is shown in Figure 5. A similar fit ($\chi^2/\text{d.o.f.} = 42.3/31$) was found for $\Delta t = 3$ yrs with $\alpha = 2.7$, but now observed 10 yrs after the end of the burst. These spectra are not as good a fit to the data as the steady-state model, but they have the advantage of a softer proton spectrum that is more consistent with particle acceleration processes (e.g., Liu et al. 2006; Reynolds 2008). The observed γ -ray flux and the calculated energy-dependent proton interaction rate allows the calculation of the 1–40 TeV energy in protons produced by Sgr A* in this model. We find this energy to be 2×10^{47} ergs and 5×10^{47} ergs for the $\Delta t = 10$ and 3 yrs fit, respectively. Assuming a constant proton production rate during the burst, this results in proton luminosities

of $5 \times 10^{38} \text{ erg s}^{-1}$ and $5 \times 10^{39} \text{ erg s}^{-1}$, respectively. We will consider the viability of these fits in the next section.

4 DISCUSSION AND CONCLUSIONS

This paper has considered the time dependence of the Galactic centre TeV source under the scenario that the γ -rays originate from protons that were accelerated close to the black hole located at Sgr A*. First, we computed the time evolution of the TeV source following the ignition of a long-lived accelerator. This experiment will also be applicable to the situation where a flare or a burst of proton acceleration occurred at some point during the accelerator's lifetime. We find that, as a result of the energy dependent diffusion rate of the protons, the shortest timescale for variability is ~ 10 yrs and occurs only for $\gtrsim 10$ TeV γ -rays. Detection of this energy dependent variability would be compelling evidence for the hadronic model and an acceleration site close to Sgr A*. If the TeV source is a result of a long-lived accelerator than it must have been operating for at least 10^4 yrs to build up the large 0.1–1 TeV flux. However, because of the strong energy dependent interaction rate of the protons with the molecular gas, the injected proton spectrum must be very hard with $\alpha = 0.75$.

We also considered the possibility that the accelerator was not long-lived and that the observed γ -rays are a result of a recent burst of particle acceleration that has since ended. This model seemed particularly interesting in light of the recent results from Fe K α reverberation indicating that Sgr A* was more luminous $\gtrsim 100$ yrs ago (e.g., Ponti et al. 2010; Terrier et al. 2010). However, we are able to definitively rule out this possibility, as there is no way that a burst of protons of any duration or spectral index can reproduce the observed photon index over 100 yrs after the end of the burst. This is because the highest energy protons produce their γ -rays within 10 yrs of being released into the interstellar medium. Moreover, if $\alpha = 0.75$ it would take several thousand years after the end of the burst to reproduce the shape of the low energy H.E.S.S. spectrum.

Considerations of how the TeV spectrum evolved with time allowed the discovery of new solution to the observed H.E.S.S. spectrum, now with $\alpha = 2.7$. This new model implies the H.E.S.S. observations were made ~ 10 yrs after a burst lasting 3–10 yrs. This model has the immediate advantage that the proton spectral index is easily accounted for by particle acceleration processes, but implies a more random and variable acceleration region. This would not be unexpected given the observed variability (on much shorter timescales) seen from Sgr A* in X-ray wavelengths. It should be emphasised that burst durations shorter than 3 yrs and (slightly) longer than 10 yrs would still be able to fit the H.E.S.S. data. The only differences from the above result would be in the delay between the end of the burst and the observation time, and in the proton luminosity produced by the accelerator (a higher luminosity would be needed for a shorter Δt). A key prediction of this scenario is that the spectrum will soften noticeably over the next ~ 5 yrs as the high energy γ -rays disappear. Of course, further short bursts of protons could continue to energise this region of the spectrum. In that case, some spectral variability in the high-energy region of the spectrum might be observed on \sim few year long timescales as the spectral index of the protons would be unlikely to be identical during each outburst.

The fits for the burst scenario imply a proton luminosity of $\sim 10^{38-39} \text{ erg s}^{-1}$. This is within an order of magnitude of the proton luminosity originally calculated by Liu et al. (2006) in their first application of stochastic acceleration of protons to the TeV

source. It is interesting to compare this power in protons to the radiative output of Sgr A*. The observed bolometric luminosity of Sgr A* is $\sim 10^{36} \text{ erg s}^{-1}$, resulting in an Eddington ratio of 3×10^{-9} . The gas density and temperature has been measured at the Bondi radius (Baganoff et al. 2003), and the resulting Bondi accretion rate is $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$ (e.g., Quataert 2004). To account for the observed luminosity of Sgr A* this flow must have an extremely small radiative inefficiency of $\sim 5 \times 10^{-6}$. Accretion models have only been able to explain this very low efficiency by reducing the actual accretion rate onto the black hole by $\sim 10^{-3}$ via strong outflows (Yuan et al. 2003; see also Sharma et al. 2007). These low accretion rates seem to be consistent with those derived from sub-millimetre polarisation measurements (e.g., Marrone et al. 2007), although care is needed in the interpretation of those data (e.g., Ballantyne et al. 2007b). If the TeV source is generated by brief bursts of particle acceleration in the accretion flow, then this could be another mechanism of reducing the radiative efficiency of weakly accreting black holes. There already exists compelling evidence that at very low inflow rates the liberated accretion energy can be efficiently converted into particle acceleration. For example, the presence of jets is much more common in low-luminosity AGNs than in other, more luminous accreting black holes (e.g., Ho 2008). Similarly, accreting stellar mass black holes are observed to preferentially produce jets at low Eddington ratios (e.g. Fender 2001; Maccarone 2003; Gallo et al. 2006). At even smaller accretion rates (but very high black hole mass), there seems to be an efficient conversion of accretion power into jet power (Allen et al. 2006). The radio and sub-millimetre emission from Sgr A* can also be described as originating from a mildly relativistic jet (e.g., Falcke et al. 2009; Maitra et al. 2009). The TeV source from the Galactic centre could be another indication that weakly accreting black holes are important sites of particle acceleration, where, in this case, the efficiency of conversion into proton power would be $\sim 10^{-3} - 10^{-4} \dot{M}_{\text{Bondi}}$.

In our exploration of the time-dependence of the γ -ray signal from the Galactic centre, we have found two potential explanations for the source. The first requires a long-lived particle accelerator, lasting at least 10^4 yrs, and a very hard proton injection spectrum of $\alpha = 0.75$. The 10^4 yrs timescale is the minimum required for protons to diffuse throughout the Galactic ridge and contribute to the observed TeV glow of the inner galaxy (Aharonian et al. 2006a). In addition, Crocker et al. (2007) found that the interaction of the $\alpha = 0.75$ proton spectrum with the stellar wind gas in the Galactic centre naturally accounted for the observed GHz radio emission from that region. The proton luminosity required from this particle accelerator would be $\lesssim 10^{34} \text{ erg s}^{-1}$ and would indicate that particle acceleration would not be an important energetic component of the accretion flow, perhaps consistent with the small fraction of non-thermal electrons needed to fit the Sgr A* spectrum (e.g., Yuan et al. 2003).

The rapid burst scenario reproduces the observed spectrum with a more typical proton spectrum of $\alpha = 2.7$, but requires the H.E.S.S. observations to have been made at specific times after the bursts. If the bursts of particle acceleration are reasonably frequent, however, then this problem is not too constraining. Perhaps the cleanest discrimination between the two scenarios is that a much higher degree of spectral variability would be expected in high energy γ -rays in the burst model than for the long-lived accelerator. In the former case, the high energy spectrum should soften dramatically over the next few years unless additional bursts have re-energised the high energy particles. The long-lived accelerator would be expected to only show moderate variability in response

to changes in the acceleration rate and, at high energies, this would be at decade-like timescales. If any spectral variability of the TeV spectrum is observed, then this would be strong support for the hadronic model. To conclude, we recommend that spectral monitoring of the Galactic Centre TeV source should be performed on an annual basis to search for spectral variability, with particular emphasis in searching for changes in the > 10 TeV spectrum. Improving the quality of the observations at > 10 TeV will be extremely important in determining the mechanism behind the TeV source.

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